Welding Metallurgy

Metallurgical Effects of the Weld Thermal Cycle

Lecture Scope

- Metallurgical phenomena involved in welding
- Effects on weld and HAZ properties

Weld and Heat Affected Zone

A welded joint consists of:

- weld metal
  - melted and re-solidified base metal mixed with filler metal (if added)
- heat affected zone (HAZ)
  - the region around the weld whose properties or microstructure are affected by the thermal cycle
  - reheating also alters the structure of underlying weld metal in multi-pass welds
- and base metal

Metallurgical Phenomena

- Welding is a complex process that involves:
  - Gas-metal & slag-metal reactions
  - Solidification
  - Metallurgical reactions in the solid state
    - annealing & recovery
    - grain growth
    - precipitation
    - phase transformation
- These metallurgical phenomena control weld strength and ductility

Gas-Metal Reactions

- Reactive gases (especially N_2, O_2, H_2) may be present in the arc atmosphere due to surface contamination, imperfect shielding, or purposeful additions.
- These gases dissociate in the arc and react rapidly with the high temperature, turbulent liquid metal in the weld pool.
- Once dissolved in the metal, oxygen and nitrogen combine with deoxidizers such as Si or Al. The resulting oxides or nitrides remain as small inclusions in the weld metal.
- Excess dissolved gas is rejected during solidification and may cause porosity (e.g. hydrogen in Al)
- Dissolved hydrogen can cause cracking in steels

Slag-Metal Reactions

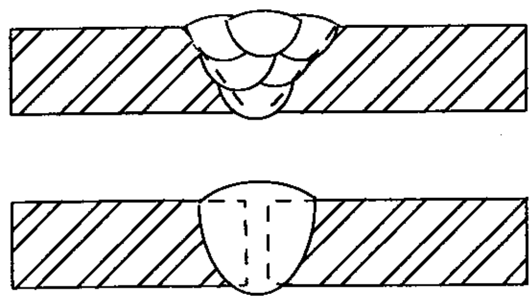
- Fluxes and slags interact with the molten weld metal
- The slags used in flux shielded processes are designed to absorb deoxidation products and other contaminants
- The cleanliness and properties of the weld metal depend on the oxidation potential of the arc atmosphere and on the type of flux
- Highly basic fluxes reduce weld metal oxygen content and give superior notch toughness. Acid fluxes tend to give higher oxygen contents and poor notch toughness.
- Fluxes may also be used to modify weld metal composition by transfer of alloying elements from the slag to the liquid metal

Dilution

- Dilution results from mixing of filler and base metals
  - .Dilution ratio is the mass of base metal melted divided by the total mass of melted metal
- Weld pool mixing results in a uniform fused zone, except when large differences exist between filler and parent composition
- A sharp boundary lies between the fused zone and base metal
- Dilution is influenced by joint preparation, welding process and procedure

Low dilution

High dilution

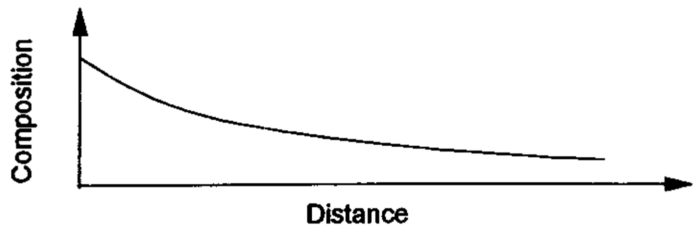


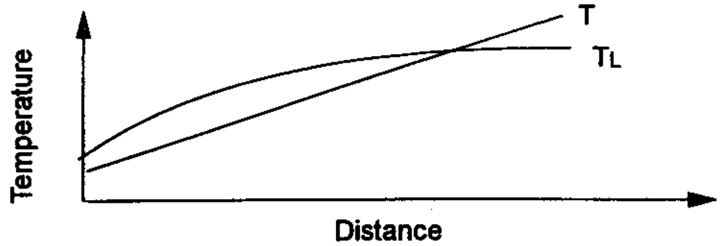
Solidification

- Factors controlling the solidification modes of metals are:
  - temperature gradient
  - composition
  - rate of solidification

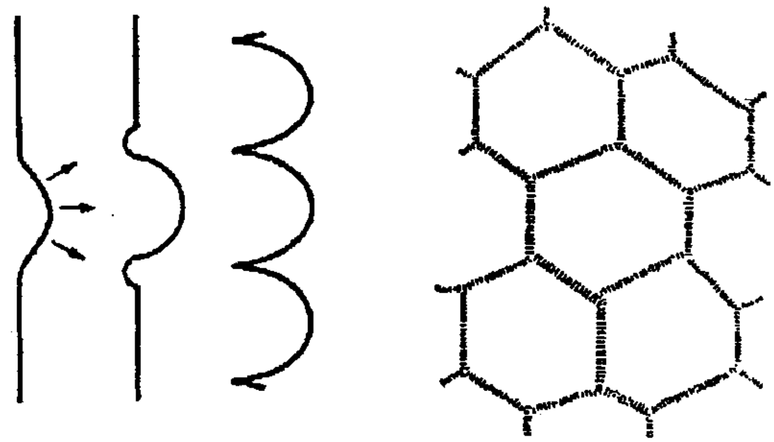
Constitutional Undercooling

The variation in composition, temperature, and freezing temperature in front of a solid liquid interface can make a plane interface unstable





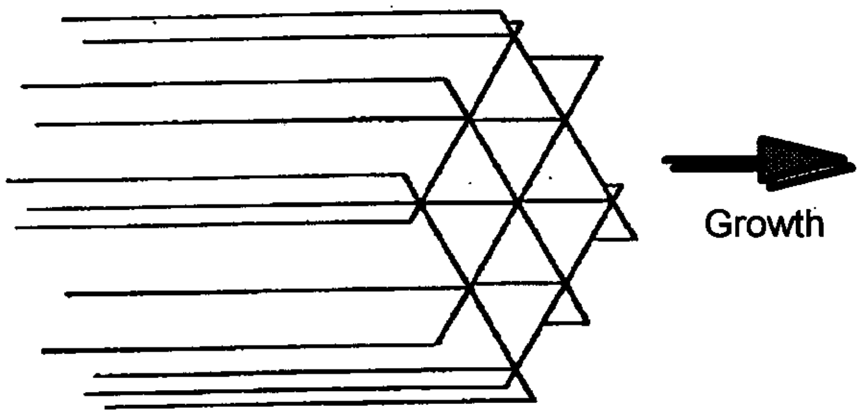
Cellular growth



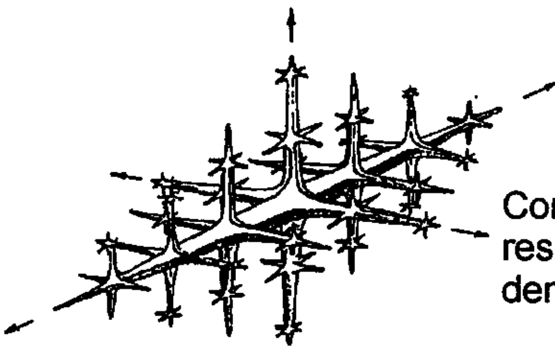
A bulge in the solid projects into the more undercooled liquid and so grows more. One effect is the cellular structure shown

Cellular Dendrite

Greater undercooling, e.g. due to reduced temperature gradients, produces a cellular dendritic structure

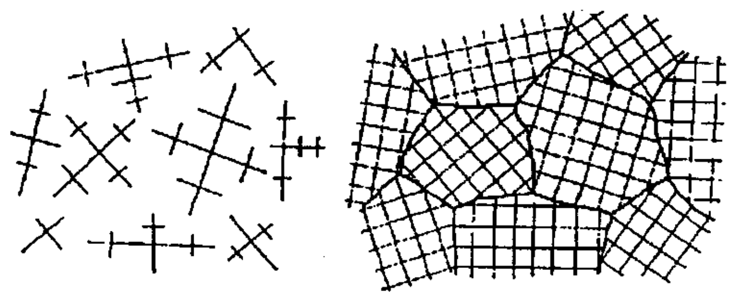


Equiaxed dendritic growth



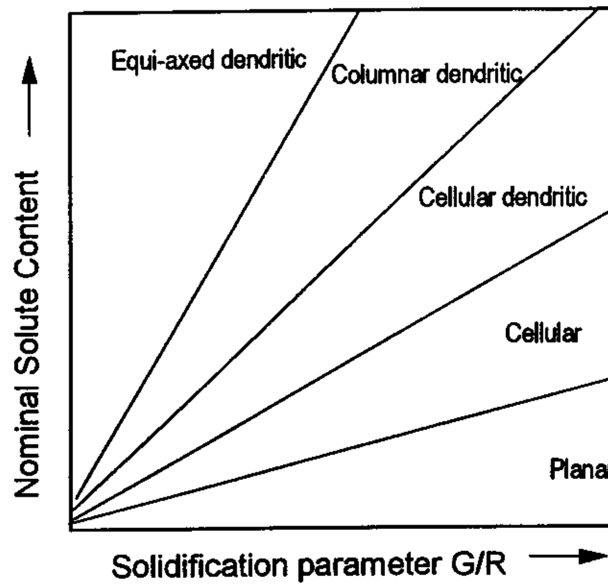
Dendrite

Continued increases in undercooling result in solidification of the melt by dendrite formation and growth



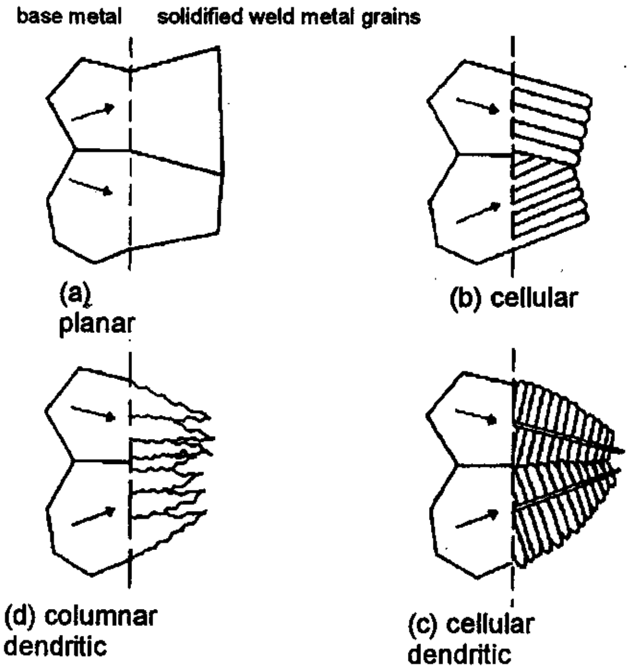
Solidification Modes

Factors controlling crystal growth mode



- G = Temperature gradient in direction of solidification
- R = Rate of advance of solidification front

Epitaxial Growth



- The crystals in solidifying weld metal nucleate on grains in the surrounding solid.
- Crystals whose orientations are favourable for growth dominate.
- Termed "competitive epitaxial growth."
- Results in a directional solidification structure.

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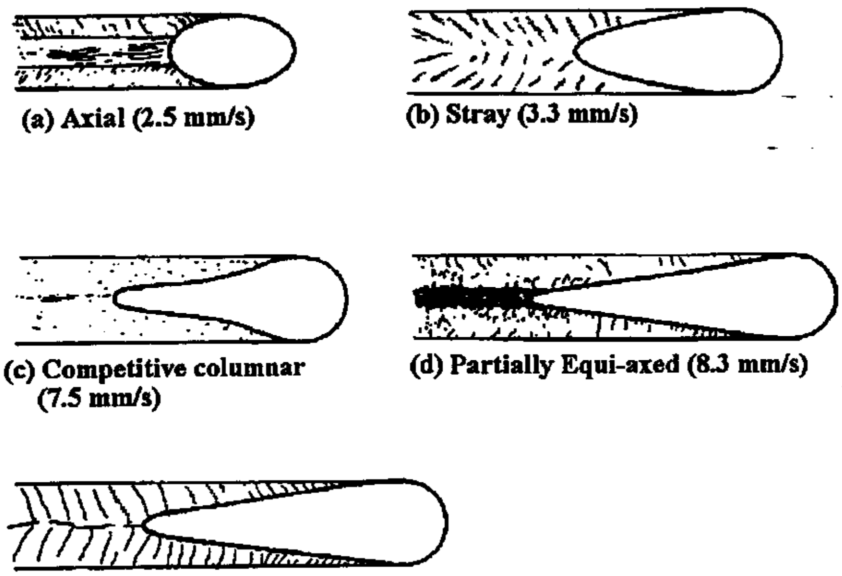
Weld Solidification Macrostructure



(a) Axial (2.5 mm/s)

(b) Stray (3.3 mm/s)

(c) Competitive columnar (7.5 mm/s)

(d) Partially Equi-axed (8.3 mm/s)

(e) Centreline (16.7 mm/s)

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Reactions in the solid phase

- Annealing, recrystallization & grain growth
- Precipitation hardening
- Phase transformation

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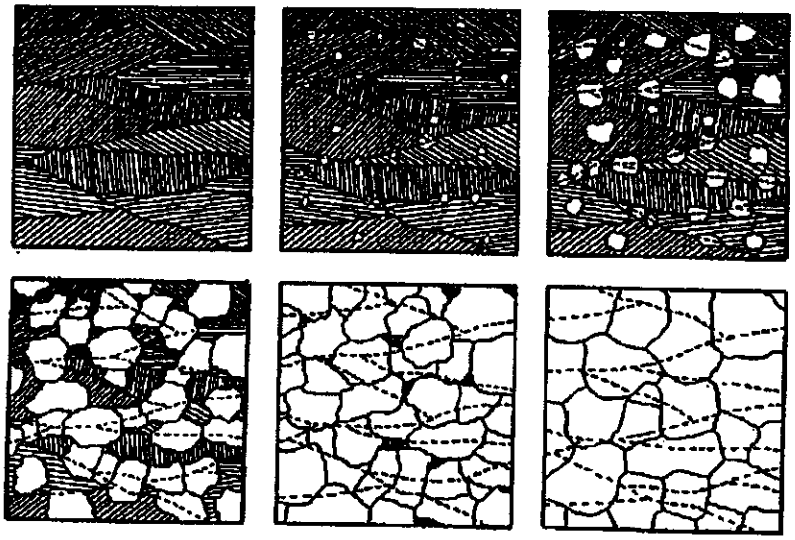
Annealing and Recrystallization

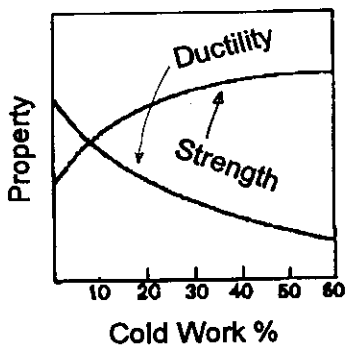
- Welding has little effect on the properties of ***annealed*** single phase alloys that are strengthened by ***solution strengthening***
  - e.g. hot rolled low carbon steels, austenitic stainless steels, commercially pure aluminum, titanium and zirconium.
- However, when such materials are strengthened by cold work, the weld thermal cycle induces recrystallization and grain growth
- The welding heat anneals the heat affected zone, reducing its strength and increasing ductility

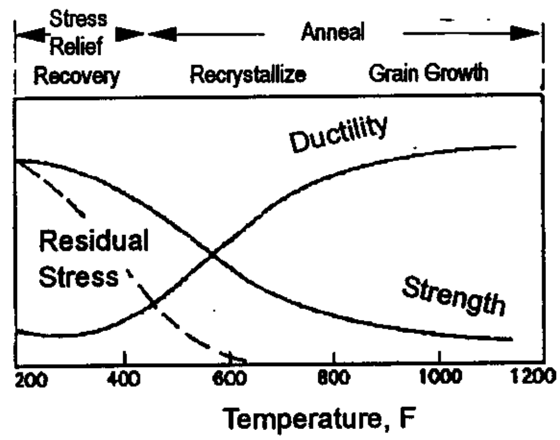
Stages in Recrystallisation



Top from left: cold worked grains, nucleation of new undeformed grains
Bottom: growth of new grains, completely recrystallized microstructure

Effect of Cold Work and Annealing

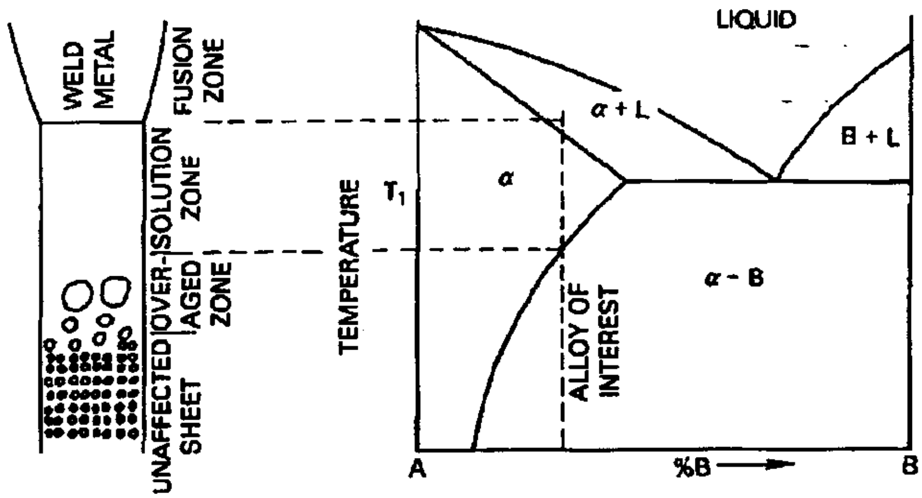




Precipitation Hardening

- ***Precipitation hardening*** alloys are strengthened by fine precipitates dispersed in the matrix
  - Al, Cu, stainless steel
- PH alloys are hardened by heating to a high temperature, at which the solutes are taken into solution, and quenching, followed by ageing at a lower temperature to permit the development of fine precipitates.

Weld & HAZ in PH alloys



Effects of Welding on PH Alloys

- The weld thermal cycle disrupts the microstructure of alloys welded in the hardened condition
- The weld metal and high-temperature HAZ are in effect solution treated.
- In parts of the HAZ that reach temperatures below the solution temperature, the precipitates coarsen, causing loss of strength. This over-ageing can be recovered only by full heat treatment
- However, precipitation hardening alloys can be welded with reasonable success in the solution-treated condition, followed by an ageing treatment after welding

Phase Transformations

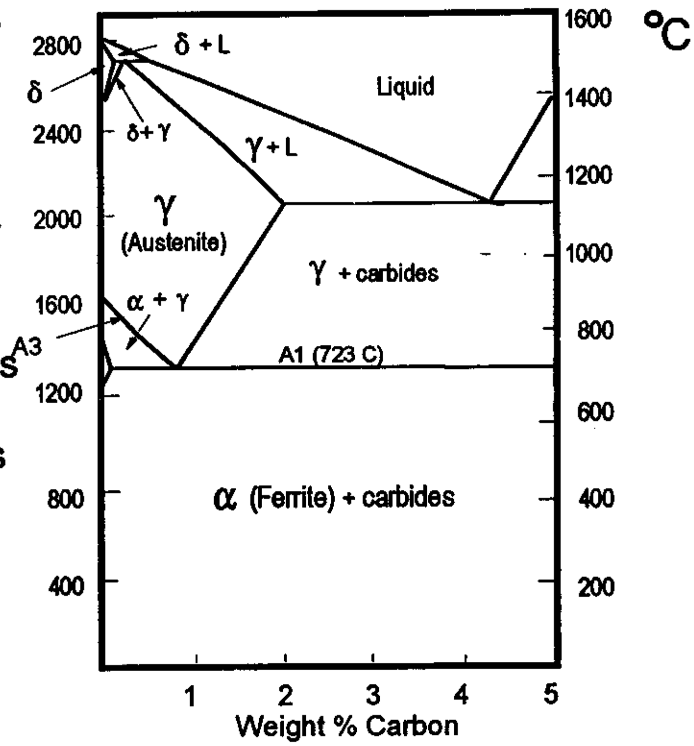
- The properties of steels are influenced by the phase transformations they undergo on heating and cooling
- Iron solidifies as a body-centred crystal structure named delta-ferrite
- On further cooling it transforms to a face-centred cubic crystalline phase called gamma iron or austenite
- The austenite subsequently transforms back to a body-centred cubic form known as alpha iron or ferrite

Phase Transformations

- Austenite can dissolve up to 2% carbon, whereas ferrite can hold only 0.025% carbon in solution
- On transformation to from austenite to ferrite, carbon in solution in austenite in excess of 0..025% forms carbide precipitates.
- The austenite to ferrite transformation and the behaviour of carbon are the most important determinants of the properties of steels.

Fe-C Phase Diagram

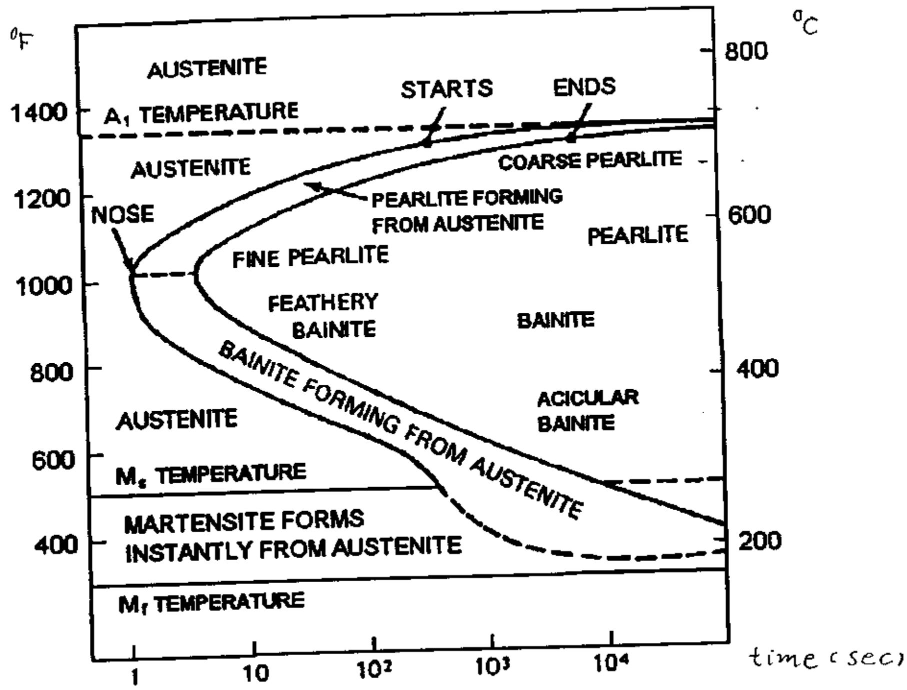
- The concentration of carbon alters the temperatures at which phase changes occur.
- This phase diagrams show the equilibrium phases at various compositions and temperatures



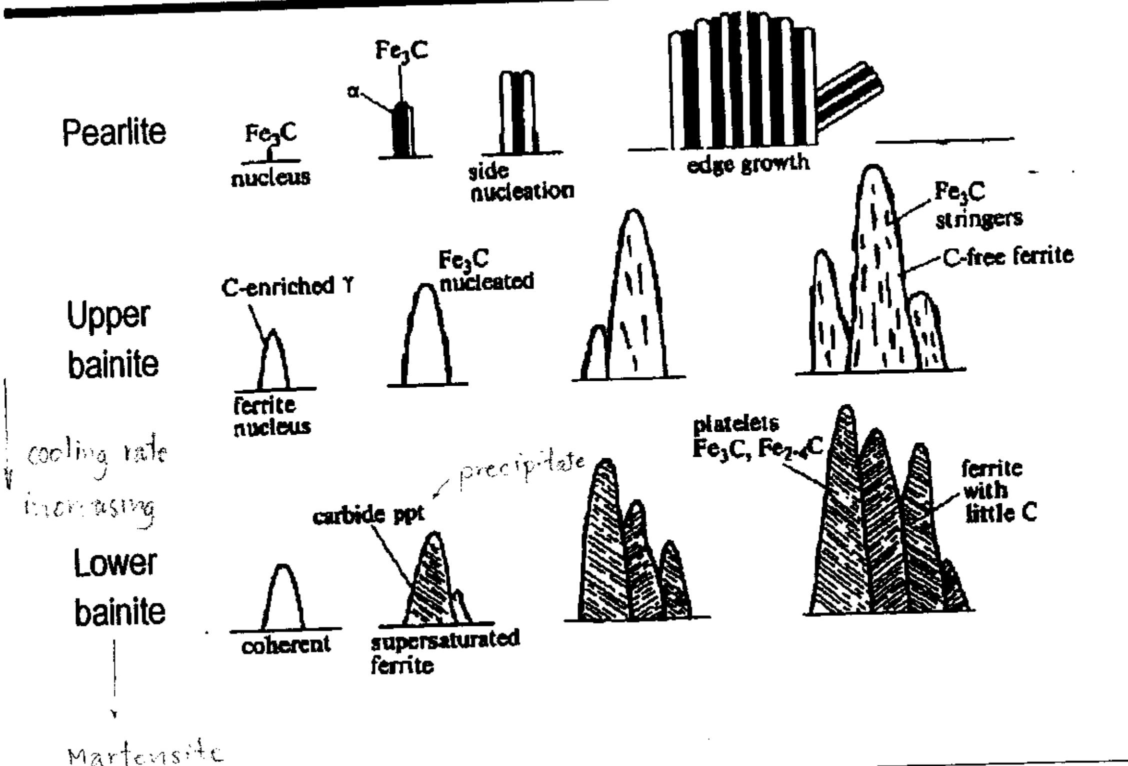
Kinetic effects

- During rapid heating and cooling, non-equilibrium phase structures develop.
- The iron-carbon phase diagram does not provide information about:
  - the transformation of austenite to non-equilibrium phase structures,
  - give details on the kinetics of transformation,
  - show the relationship between transformation temperature and products.
- The time-temperature transformation diagram (TTT diagram) is useful for these purposes

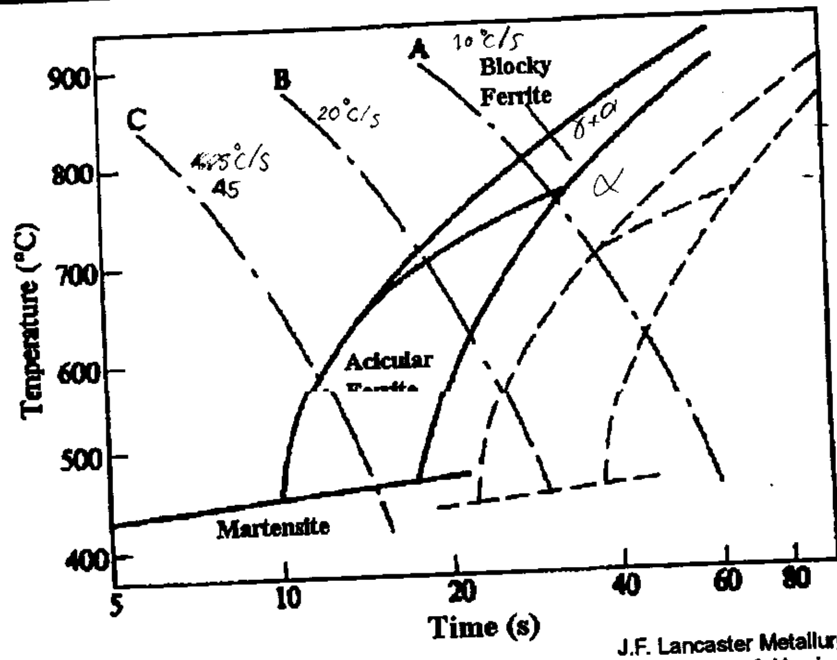
TTT Diagram (0.8% C steel)



Transformation products in steel



Continuous Cooling Transformation (CCT) Diagram



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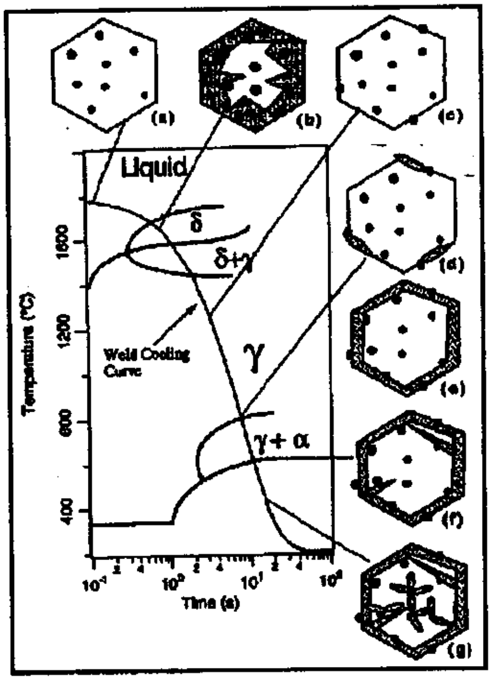
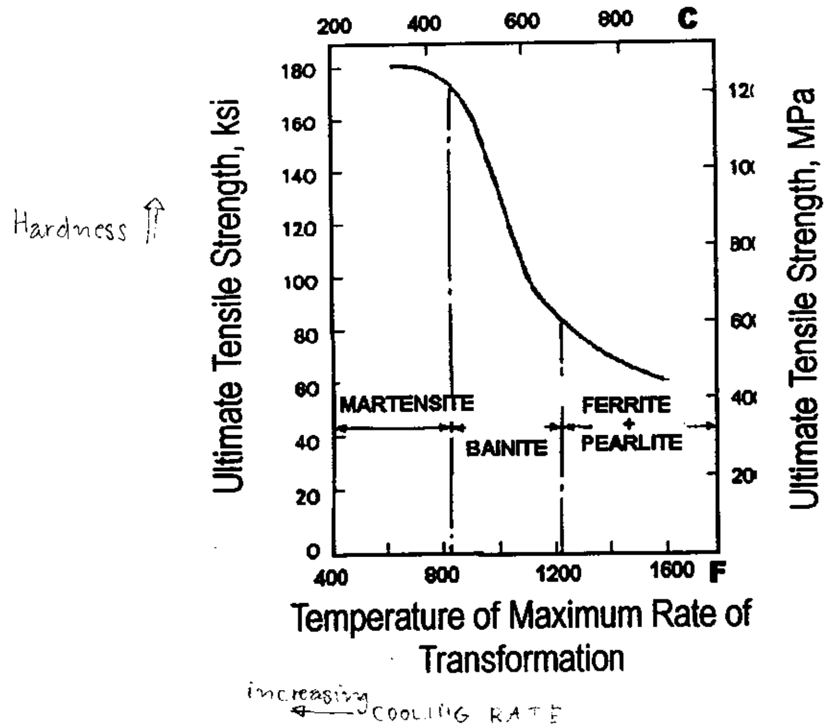
CCT diagram

a. inclusion formation
b. solidification of liquid to delta ferrite
c. fully austenitic structure
d. nucleation of ~~allotriomorphic~~ ferrite
e. growth of ferrite
f. Widmanstatten ferrite formation
g. acicular ferrite formation

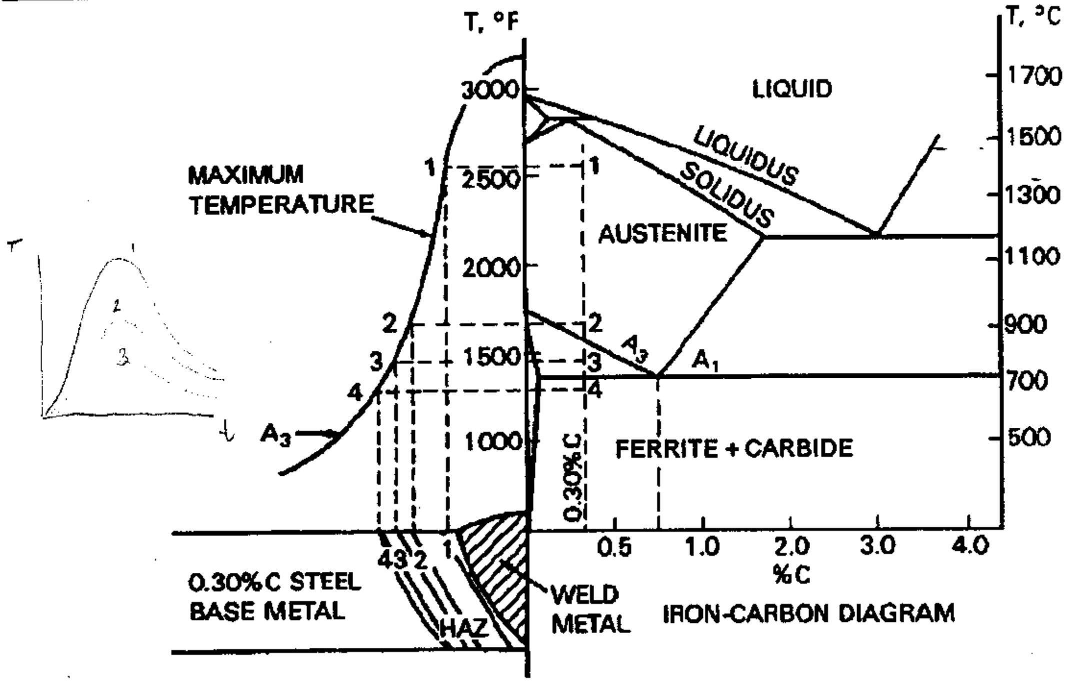


K. Mundra, T. DeBroy, S.S. Babu and S.A. David: Welding Journal Research Supplement April 1997, 163s-171s

Effect of Transformation Temp



HAZ Structure in Steels



HAZ Structure in Steels

- In the preceding figure, Regions 1 and 2 were heated above A3 and were transformed fully into austenite and back on cooling
- Region 1 exceeded the temperature at which the carbide particles that pin the austenite grain boundaries dissolve, causing austenite grain growth
- Region 3 was heated between the A1 and A3 temperatures and partially transformed to austenite
- Region 4 did not exceed A1 and is termed the "sub-critical HAZ." Some annealing or tempering may occur in this region.

METALLOGRAPHY OF WELDS IN CARBON-MANGANESE STEELS

Slide set number 7

INTRODUCTORY NOTES

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INTRODUCTION

Steels alloyed with carbon (C) (0.1-0.25%) and manganese (Mn) (1-2%) are used in many applications as economical constructional materials, and are often welded.

The mechanical properties of weld metals in C-Mn steels (such as strength and toughness) are determined primarily by microstructure, which is dependent on factors such as chemical composition, thermal history and the type and quantity of any non-metallic inclusions. The microstructure is revealed by the standard metallographic technique of sectioning, polishing and etching, followed by examination under a microscope. The normal etchant is nital (2% nitric acid in ethyl alcohol, requiring established safety precautions), and was used in the preparation of all the samples except that shown in slide 0706.

In assessing the properties of C-Mn steel weld metals, it is important to be able to recognise the various microstructural types; these slides illustrate their normal appearances.

The terminology for describing weld metal microstructures can vary considerably, but this chart follows that currently proposed by the International Institute of Welding (Commission IX-J).

The second part of this slide set deals with the effect of welding on the adjacent unmelted parent metal designated the heat affected zone or HAZ.

HAZ microstructures in C-Mn steels are governed by the steel chemistry and the thermal cycle experienced. Increases in the alloy content, the peak temperature, time at peak temperature and the cooling rate through the transformation temperature range will all promote the formation of higher hardness constituents in the microstructure. The thermal cycle at any point in the HAZ is highly dependent on the heat input and the distance from the fusion boundary. As this reduced, giving progressively softer micro-structures. This is shown in slide 0712, which illustrates the whole heat affected zone, starting with the fusion boundary on the left.

C-Mn weld metals are:

ACICULAR FERRITE

Acicular ferrite consists of small laths of ferrite, of low aspect ratio, which occur in several distinct orientations, and which therefore give the appearance of an interlocking microstructure. This microstructure is usually associated with excellent toughness. The laths are formed in intragranular regions, and it is believed that transformation is nucleated at fairly high temperatures (about 800°C).

FERRITE WITH ALIGNED MARTENSITE/AUSTENITE/CARBIDES (M-A-C)

This microstructure can be easily distinguished from acicular ferrite, because the individual laths lie parallel to each other, have a much larger aspect ratio, and are usually nucleated at an austenitic grain boundary. One or more minor phases (martensite, austenite and carbides) are always found on the interlath boundaries. Ferrite with aligned M-A-C is generally associated with poor toughness, except in lower strength welds.

FERRITE-CARBIDE AGGREGATES (INCLUDING PEARLITE)

In high heat input welds, which have a slow cooling rate, formation of polygonal ferrite leads to rejection of carbon by the advancing transformation interface, and eventually the carbon content can rise sufficiently to transform by eutectoid decomposition, giving either pearlite or a ferrite/carbide aggregate containing equiaxed carbides in a ferritic matrix.

Continued overleaf

POLYGONAL FERRITE

Grain Boundary Ferrite

Intragranular Ferrite

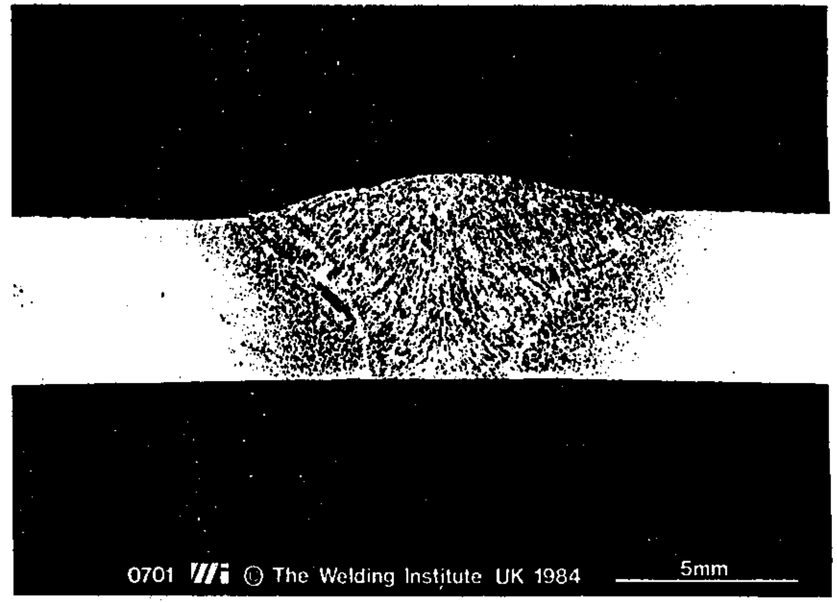
Polygonal ferrite can nucleate both at austenite grain boundaries, and in intragranular regions. It is the product of transformation at high temperatures, and its formation is therefore favoured in high heat input welds. Large amounts of grain boundary polygonal ferrite are not generally considered beneficial for toughness, especially in higher strength steels, although intragranular polygonal ferrite is never present in sufficient quantity to influence properties significantly. It is generally of lower strength than other transformation products.

MARTENSITE

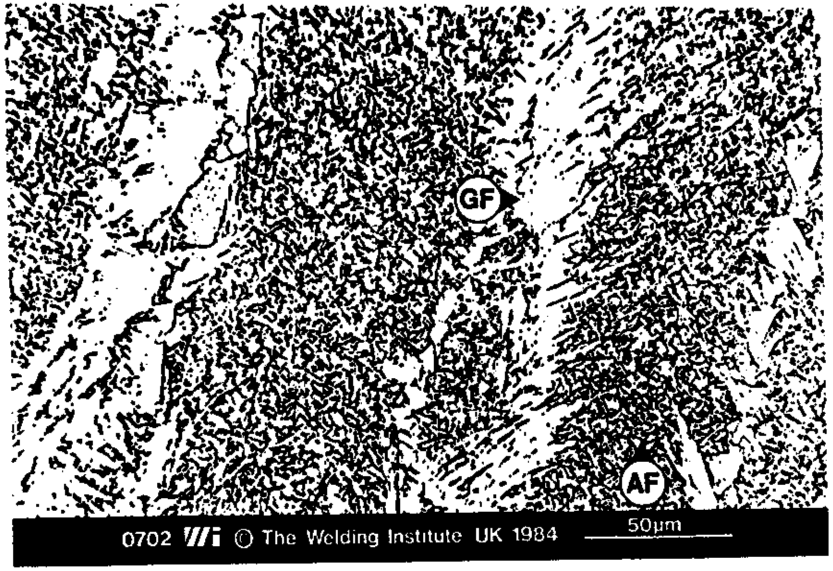
Complete transformation of C-Mn steel weld metal to martensite is unusual, but not unknown. It can happen in conditions where the cooling rate is artificially enhanced (i.e. in underwater welding), and is promoted by the use of low heat input. The toughness is generally very poor, and the strength very high.

MINOR PHASES

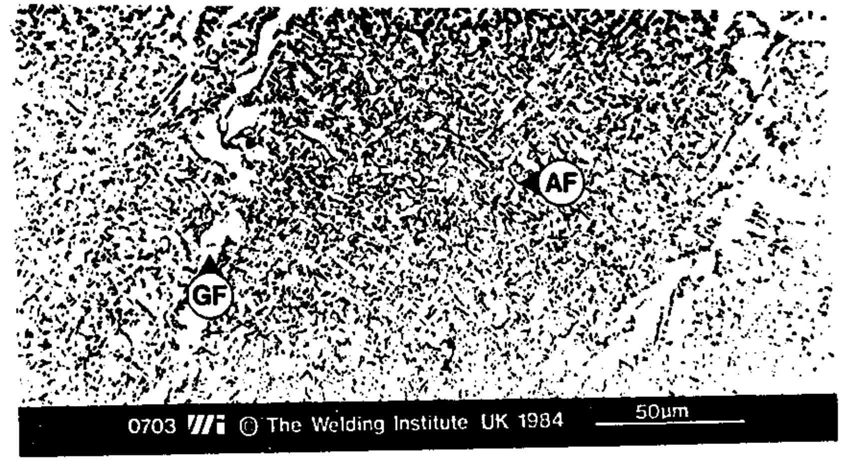
Because of segregation during solidification, the last regions to solidify often have a much higher content of alloying elements than the rest of the weld; such regions do not always transform from austenite, or may transform at such a temperature that martensite is formed.



In all fusion welding processes, the weld metal exhibits a predominantly columnar grain structure, elongated in the direction of maximum heat flow from the weld. The grain structure revealed by the usual nital etch does not represent the solidification structure, but rather the structure of the austenite grains when they started to decompose to ferrite (prior austenite structure). The solidification structure can be revealed by suitable segregation-seeking etches, and shows a very much finer structure than the austenitic grain structure. Retained phases usually lie on solidification boundaries.



The micrographs above and on the next page show acicular ferrite, **AF** and grain boundary ferrite **GF**. Note the interlocking appearance of the acicular ferrite, its low aspect ratio, and the fairly clearly defined orientations along which the laths lie. The amount of grain boundary ferrite can vary considerably.



FERRITE WITH ALIGNED M-A-C

0704 © The Welding Institute UK 1984

The micrographs above and below show typical examples of ferrite with aligned M-A-C **AC**. The appearance of this phase can vary substantially as shown in these two examples.

0705 © The Welding Institute UK 1984

RETAINED MARTENSITE AND AUSTENITE

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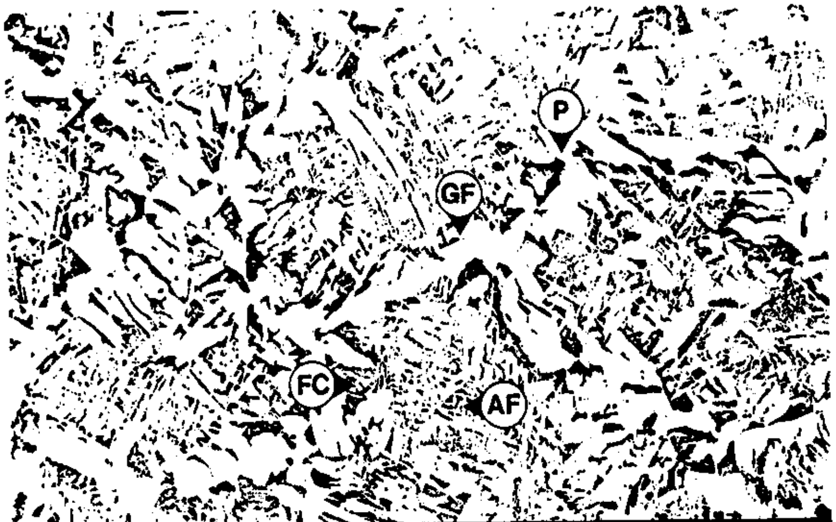
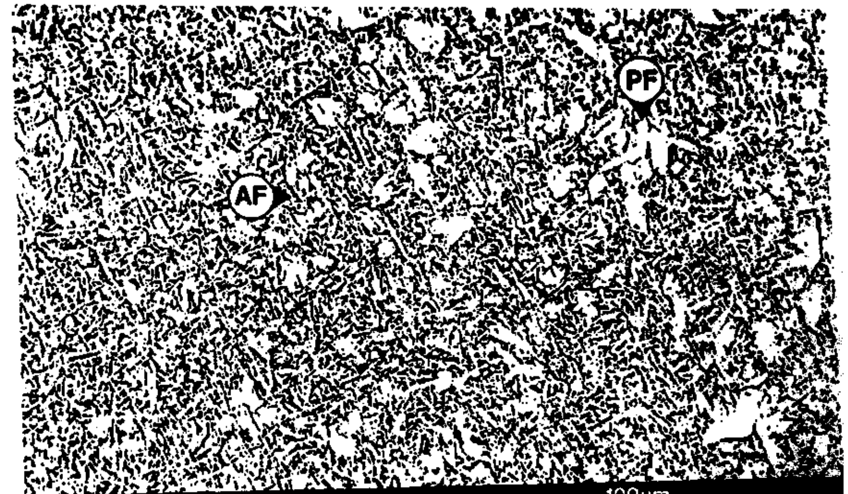
The presence of 'retained' phases (austenite and martensite) is revealed using a picral (5% picric acid in ethyl alcohol) etch. The volume fraction of these phases can be quite substantial, but they are often difficult to detect if conventional nital etches are used.



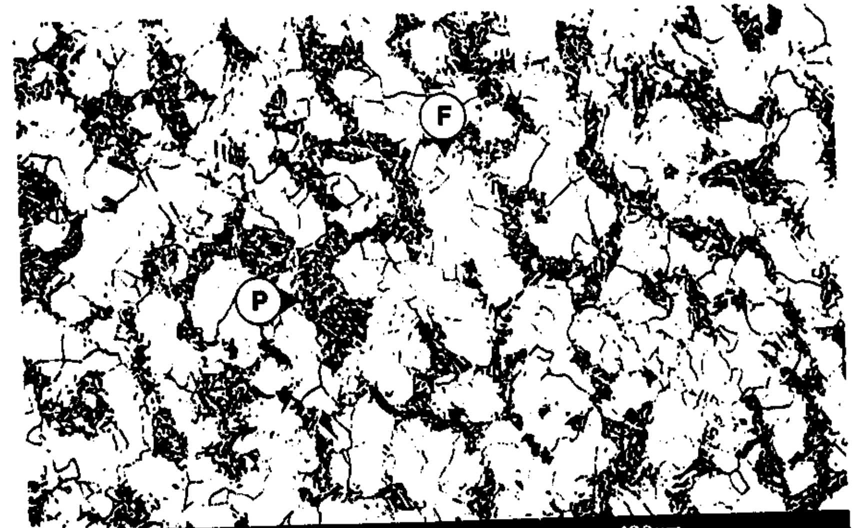
0707 TWI © The Welding Institute UK 1984 100μm

The above microstructure, from a high heat input electroslag weld, shows development of grain boundary ferrite **GF** and pearlite **P** on austenite grain boundaries, and both acicular ferrite and ferrite with aligned M-A-C in intragranular regions. Other ferrite carbide aggregates **FC** which etch lighter than pearlite can also be seen.



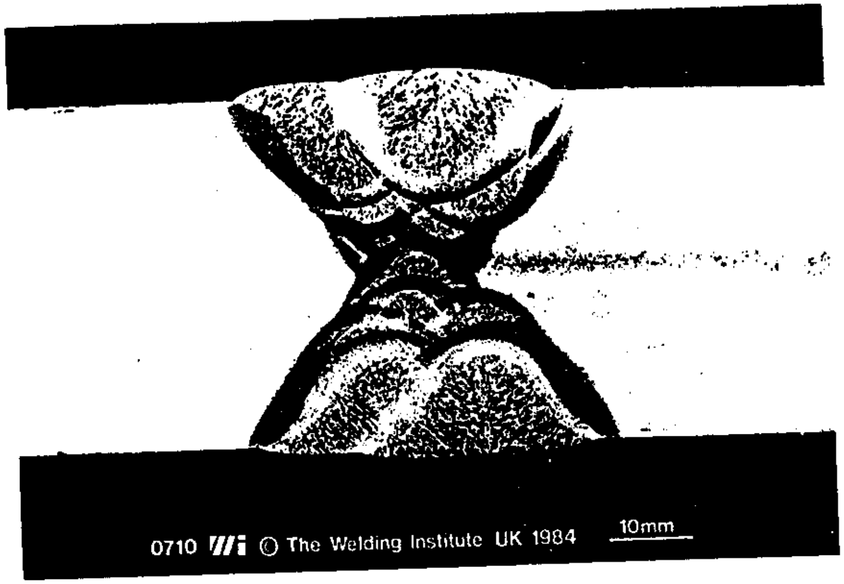
0708 TWI © The Welding Institute UK 1984 100μm

This micrograph, again from a high heat input electroslag weld, shows isolated regions of polygonal ferrite **PF** in a matrix of acicular ferrite. Because of the slower cooling rate, greater carbide rejection has occurred during transformation, resulting in small colonies of pearlite being formed between the individual ferrite laths. Note that the acicular ferrite is much coarser in this example than in others in this series, which were made at lower heat input.



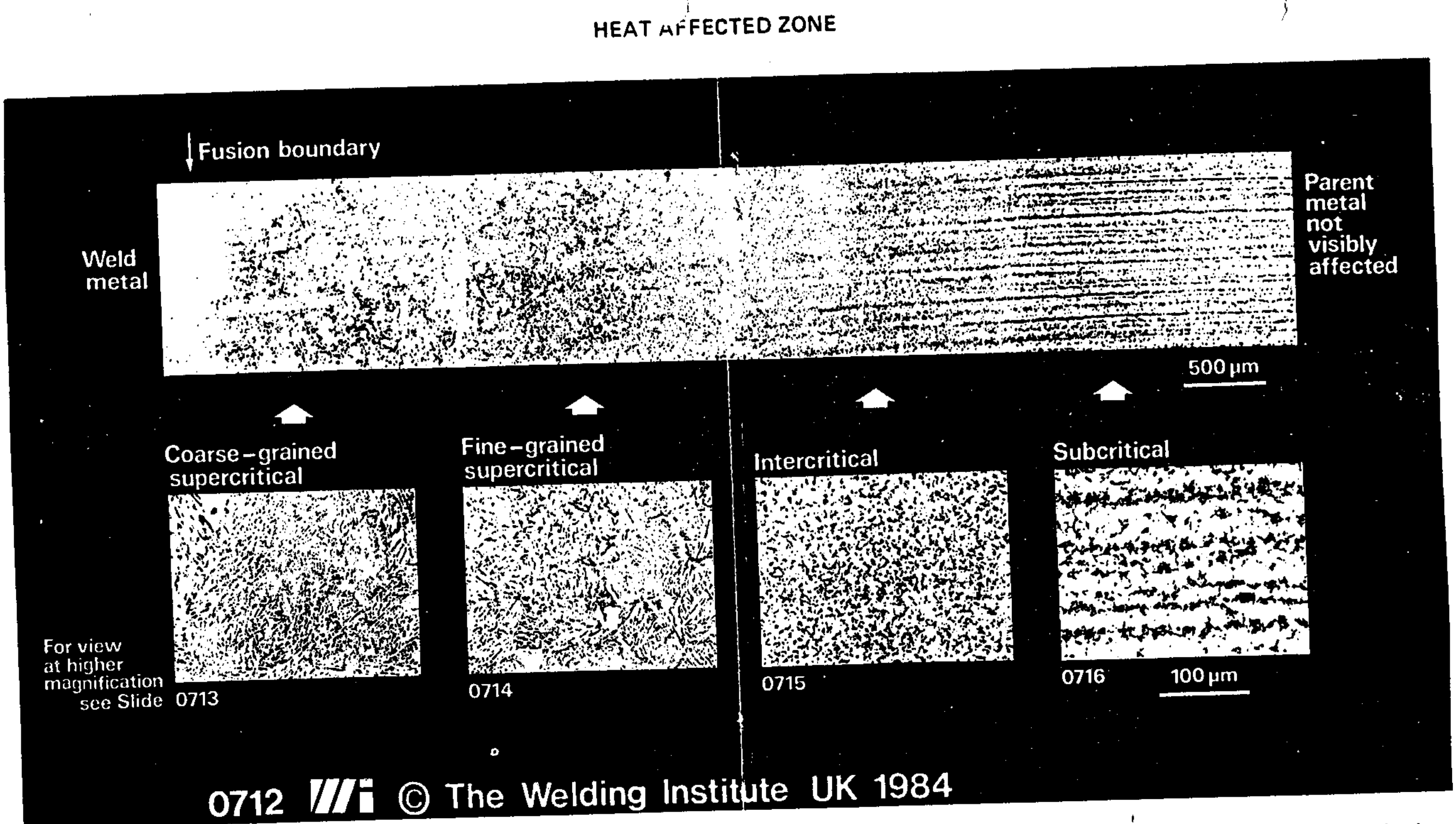
0709 WI © The Welding Institute UK 1984 100µm

Conventional post-weld normalising does not give such a fine microstructure as normalising by subsequent welding, as the thermal cycle is much longer. This microstructure, from a thick section plate, shows a typical ferrite **F** pearlite **P** structure. The pearlite regions are generally associated with the solidification boundaries, more noticeably in high heat input welds where initial segregation is probably greater. Stress relief by heat treatment is not readily visible in the microstructure. It can lead to transformation of retained phases, precipitation of carbides etc., and spheroidisation of pearlite in high heat input welds.

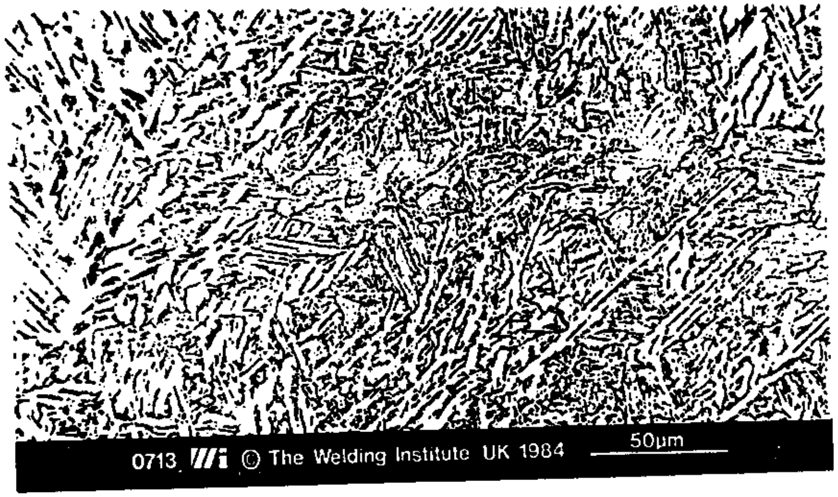


Where a joint is welded in more than one run, the microstructure of the early runs can be completely altered by the heat from subsequent passes. Where the temperature rises above a critical value (Ac_3) in the region of 875°C, then complete transformation to austenite will occur, which results in a refined structure which is essentially similar to a normalised structure, i.e. containing only equiaxed ferrite and carbides. As the thermal gradients due to successive passes are steep, the microstructures in reheated regions can vary considerably over short distances.

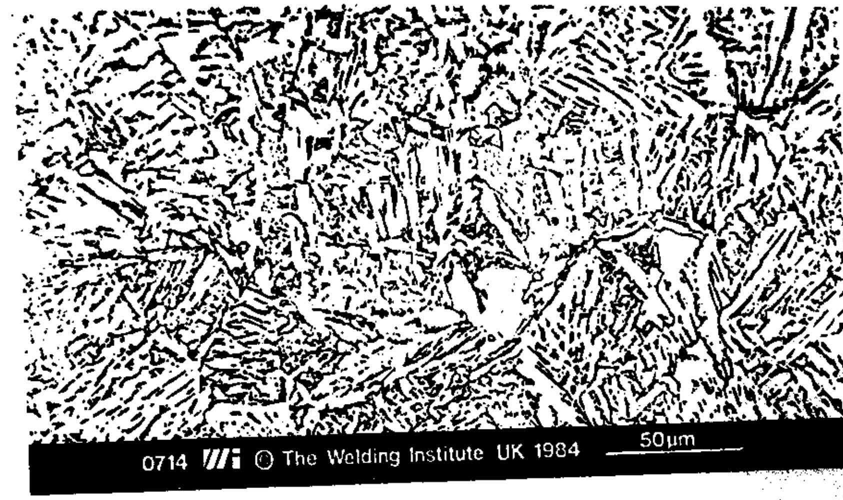
Weld metal which has been reheated above Ac_3 by a subsequent weld pass has a rapid thermal cycle, resulting in a very fine ferritic transformation structure. Such a microstructure is normally associated with very good toughness.



The thermal cycle at any point in the HAZ is highly dependent on the heat input and the distance from the fusion boundary. As this distance increases, the peak temperature and cooling rate through the transformation range are reduced, giving progressively softer microstructures. This is shown above, which illustrates the whole heat affected zone, starting with the fusion boundary on the left.



A view at higher magnification of part of the heat affected zone shown in slide 0712, near the fusion boundary, heated to a temperature sufficient to permit rapid austenite grain growth, typically above 1000°C.

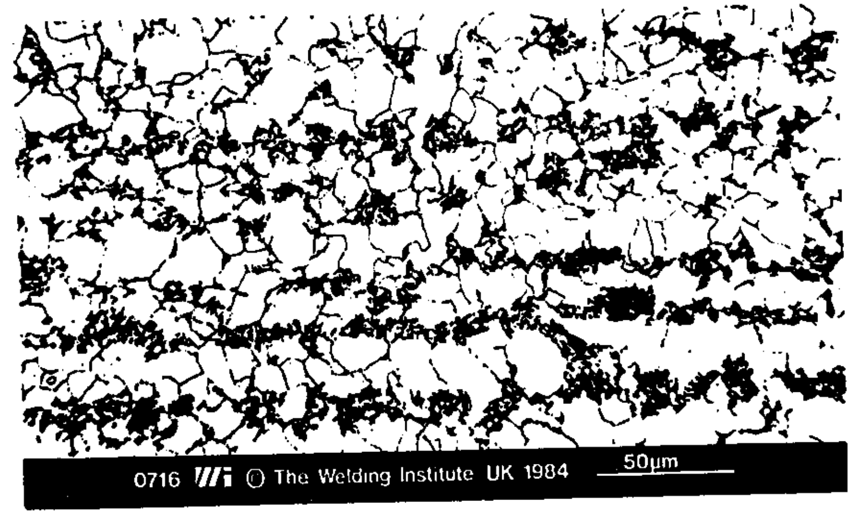


A view at higher magnification of part of the heat affected zone shown in slide 0712, towards the fusion boundary, but farther from it than slide 0713, heated to a temperature above Ac_3, but insufficient to produce rapid austenite grain growth.

INTERCRITICAL HAZ

A view at higher magnification of part of the heat affected zone shown in slide 0712, towards the parent metal, but farther from it than the next picture, heated to a temperature between Ac_1 and Ac_3, resulting in only partial transformation to austenite. Substantial refinement occurs.

SUBCRITICAL HAZ



A view at higher magnification of part of the heat affected zone shown in slide 0712, near the parent metal, maximum temperature less than Ac_1. Pearlite may be spheroidised.

MARTENSITE

Although this constituent **M** is promoted by increased alloy content, it can also be found in common C-Mn steels welded at low heat input. It is hard, usually of poor toughness, and can give rise to HAZ hydrogen cracking. Complete transformation to martensite is unusual in the HAZs of C-Mn steels, and only occurs when cooling is very rapid.

FERRITE WITH MARTENSITE/AUSTENITE/CARBIDES (M-A-C)

This is generally the predominant microstructural constituent in C-Mn steels, occurring over a wide range of heat inputs. The illustrations show that ferrite with M-A-C can have an aligned **AC** or non-aligned **FN** appearance, but this variation is probably largely a sectioning effect.

INTRAGRANULAR WIDMANSTATTEN FERRITE

Intragranular Widmanstatten ferrite **WF** may be formed with high heat input. It can be distinguished from ferrite with M-A-C by the small aspect ratio of the ferrite laths, and the characteristic basket weave type of structure. It resembles acicular ferrite commonly found in weld metal. Intragranular Widmanstatten ferrite forms at higher transformation temperatures, and is favoured by the slower cooling rates associated with high heat input.

PRO-EUTECTOID FERRITE

This constituent **FP** is often formed on prior austenite grain boundaries, especially with high heat input. Its formation is suppressed by alloying elements which lower the austenite decomposition temperature.

Continued overleaf

This con. .uent **P** is associated with very high heat input, such as in electroslag welding, and is suppressed by alloying elements which depress the austenite decomposition temperature. It is generally found only in association with pro-eutectoid ferrite.

FERRITE-CARBIDE AGGREGATES
This phase **FC** appears in regions away from prior austenite boundaries, and is the result of the eutectoid decomposition reaction. At very high magnifications, it appears as a dispersion of carbides in ferrite.

TYPICAL MICROSTRUCTURES IN HEAT AFFE ED ZONES

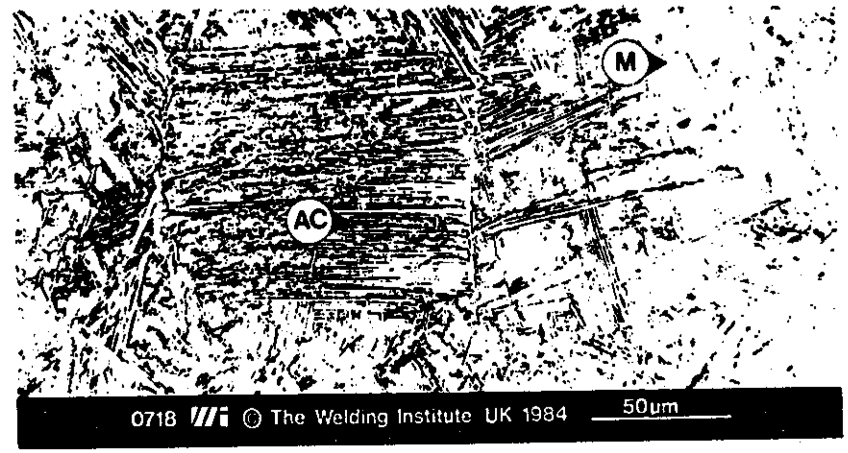
Slides 0712-0716 show one HAZ with a limited range of cooling rates; the following six photographs, slides 0717-0722, illustrate a wide range of HAZ microstructures arranged in order of cooling rate, starting with the most rapid.

Most rapid cooling — low heat input

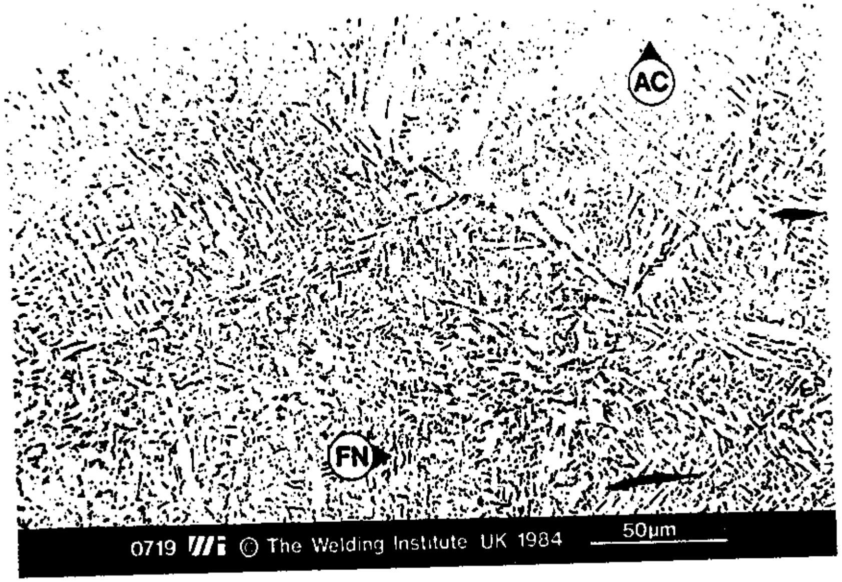
0717
0718
0719
0720
0721
0722

Least rapid cooling — highest heat input

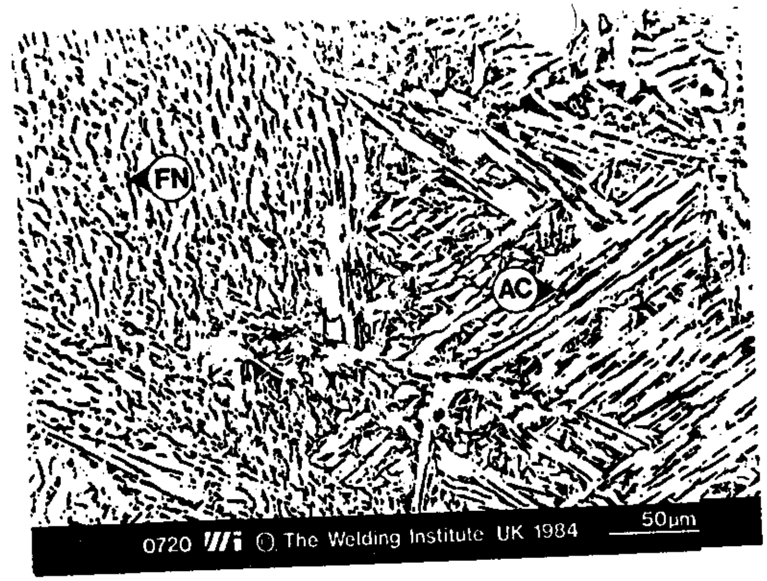
In this example, transformation to martensite is virtually complete.



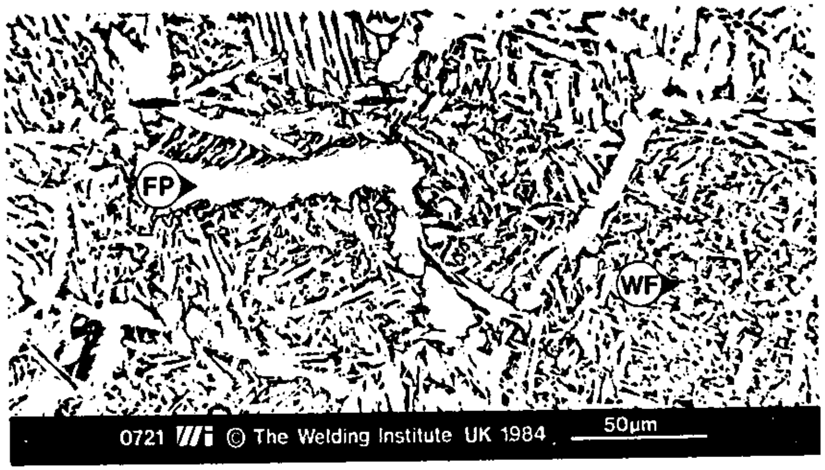
The ferrite with aligned M-A-C, **AC**, is nucleated primarily at prior austenite grain boundaries. Martensite **M** is also present.



Fine ferrite with M-A-C, showing aligned **AC** and non-aligned **FN** modes. In this example, grain boundary ferrite is suppressed.



Coarser ferrite with M-A-C than in slide 07grain present in both modes, aligned **AC** and nc aligned **FN**.



Coarse ferrite with M-A-C is present in both aligned **AC** and non-aligned **FN** modes, as in slide 0720. Pro-eutectoid ferrite **FP** and intragranular Widmanstatten ferrite **WF** are also present.

Pearlite **P** and ferrite-carbide aggregates **FC** are shown here, in a high heat input electroslag weld: they are generally associated with a high proportion of pro-eutectoid ferrite **FP**.

KEY

Identification letters	Constituent	Discussed on page	Shown on page
AC	Ferrite with aligned M-A-C	3,23	8,27,28, 29,30
AF	Acicular ferrite	3	6,7,10, 11
F	Ferrite		13
FC	Ferrite-carbide aggregates	3,24	10,30, 31
FN	Ferrite with non-aligned M-A-C	23	28,29, 31
FP	Pro-eutectoid ferrite	23	30
GF	Grain boundary	4	6,7,8, 10
M	Martensite	23	26,27
P	Pearlite	3,24	10,13, 31
PF	Polygonal ferrite	4	11
WF	Intragranular Widmanstatten ferrite	23	30

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